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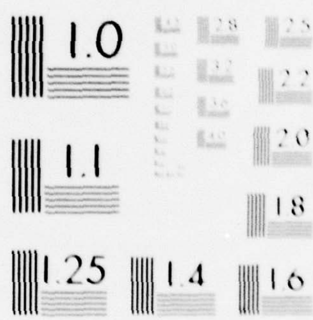
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Iowa City, Iowa 52242

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GALACTIC COSMIC-RAY INTENSITY TO A HELIOCENTRIC DISTANCE OF 18 AU

by

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Submitted for Publication to Astrophysical Journal

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ABSTRACT

An updated report is given of observations of galactic cosmic ray intensity to heliocentric radial distances of 8.6 and 18.4 AU with Pioneer 11 and Pioneer 10, respectively. Solar activity via the magnetic structure of the interplanetary medium continues to modulate the intensity out to the greatest distance reached thus far. During the period 1972-1979, aperiodic temporal variations of intensity by about a factor of two and on a time scale of the order of a year are observed as are quasi-persistent cyclic variations of 26-day period and amplitude of a few percent. The latter are associated with fast-slow solar wind streams, not with toward-away magnetic field sectors. For protons of energy $E_p > 80$ MeV, sub p there is a fairly consistent heliocentric radial gradient of +2.1 (± 0.3) percent per AU in intensity until April-May 1978, at which time a substantial disruption of the distribution of cosmic rays in the heliosphere occurred. The radius of the heliosphere is estimated to be of the order of 80 AU.

+ or -

I. INTRODUCTION

The intensity of galactic cosmic rays at 1 AU varies cyclically with a period of eleven years, in approximate synchronism with the variation of activity on the sun as characterized by mean sunspot numbers (Forbush 1954). Maximum intensity occurs near epochs of minimum sunspot number and vice versa. For protons having energies $E_p > 55$ MeV, the observed maximum-to-minimum intensity ratio in interplanetary space at 1 AU was about 1.9 during the period 1967-73 (Thomsen and Van Allen 1976).

The general view of this effect is (a) that the solar system is bathed in a nearly isotropic distribution of interstellar cosmic rays having intensity, spectral form and composition that are constant with time over periods of many, many hundreds of years; (b) that the interstellar intensity is greater than that at any point within the region of the sun's influence (the "heliosphere"); and (c) that the solar cycle modulation of observed intensities is attributable to varying magnetic properties of the interplanetary medium.

The traditional interpretation of the solar cycle modulation rests on the assumption that, at any given moment, there is quasi-equilibrium between diffusion of cosmic rays into the solar system

from the nearby interstellar medium and their outward convective transport by irregular magnetic field structures ("scattering centers") moving away from the sun in the solar wind. Such an interpretation requires an outward directed gradient of intensity. The order of magnitude of the necessary physical scale of scattering structures is suggested by the magnitude of the gyroradii of protons moving perpendicular to a magnetic field $\vec{B}$ of strength appropriate to measured values in the solar wind. At 1 AU, $|\vec{B}| \approx 5\ \gamma$ [1 gamma = 1 nanotesla = 1×10^{-5} gauss] and exemplary values of gyroradii are as follows: 100 MeV, 0.0020 AU; 1,000 MeV, 0.0076 AU; 10,000 MeV, 0.049 AU.

Thus a long standing problem in cosmic ray physics is the observational determination of (a) the heliocentric radial dependence of the intensity and of other properties; (b) the position of the outer boundary of the influence of the sun ("the heliopause"); and (c) the intensity and other properties of the radiation in the nearby interstellar medium. At the present time, the most advanced effort in this research is represented by the ongoing measurements to increasingly great distances from the sun with instruments on Pioneer 10 and Pioneer 11. In the energy range ($\geq$ 50 MeV) relevant to the present paper, earlier reports by the author (Van Allen 1972, 1976) and others (Teegarden, McDonald, Trainor, Roelof, and Webber 1973; McKibben, O'Gallagher, Simpson, and Tuzzolino 1973; Thomsen and Van Allen 1976; Axford, Fillius, Gleeson, and Ip 1976;

McDonald, Lal, Trainor, and Van Hollebeke 1977) have already shown that the heliocentric radial gradient of intensity is much smaller and that the heliopause lies at a much greater distance than expected from the traditional theory. In addition, an improved knowledge of the detailed nature of the solar modulation has been obtained (Van Allen 1976) (referred to as VA 76 hereafter). These observations together with an increasing realization of the non-spherically-symmetric nature of the interplanetary medium have stimulated fresh theoretical approaches.

II. INSTRUMENT AND OBSERVATIONAL CIRCUMSTANCES

The University of Iowa instruments on Pioneers 10 and 11 comprise, among other detectors, six miniature Geiger-Mueller tubes in three approximately-matched pairs between the two spacecraft. These detectors are shielded omnidirectionally in order to have a penetration threshold of 80 MeV for protons. Their counting rates are attributable to galactic cosmic rays, solar-emitted energetic particles, and radioactive emissions of the radioisotope thermal generators (RTG's) which provide electrical power for the spacecraft and its instruments. Contributions by the RTG's are subtracted by an improved version of the procedure described by Thomsen and Van Allen (1976). Solar energetic particles are identified with the help of other detectors having lower energy thresholds. Brief periods during which their contribution is significant are omitted as are the periods during which the spacecraft were near Jupiter. Effects of Jupiter-emitted particles have probably been identified in our data by Venkatesan, Agrawal, and Van Allen (1979) but have not been eliminated.

The trajectories of Pioneers 10 and 11 are shown in Figure 1. At the time of launch of Pioneer 11 (1973 April 6) the respective heliocentric radial distances were r_{10} = 3.94 AU

and r_{11} = 1.00 AU so that $\Delta r \equiv r_{10} - r_{11} = 2.94$ AU. The value of Δr diminished to a minimum of 1.20 AU on 1974 September 2 and thereafter has increased monotonically. The difference in heliocentric ecliptic longitude $\Delta\varphi \equiv \varphi_{10} - \varphi_{11}$ has varied widely (Figure 1).

III. REVIEW OF INTENSITY DATA AND TEMPORAL VARIATIONS

Figure 2 presents a comparative overview of the (fully corrected) counting rates of the two members of a pair of similar detectors on the two spacecraft for 1972-1979. The absolute geometric factors of the two detectors are slightly different and no normalization has been performed. Omitting the narrow spikes (solar particle events) the rate of detector C_{10} varied over the range 0.55 to 0.84 s^{-1} during the period shown while that of C_{11} varied over the range 0.43 to 0.82 s^{-1}. The gross variations in counting rates at the two spacecraft are coherent and are clearly temporal, not spatial, in nature.

Thus, a principal finding from Figure 2 is that solar activity (via the interplanetary medium) continues to have an important influence on cosmic ray intensity out to at least 18 AU.

The finer scale temporal variations of intensity during 1976, 1977, and 1978 are exhibited in Figures 3, 4, and 5, respectively. The corresponding curves for 1973, 1974, and 1975 have been published previously (VA 76). (Note that a five-day running mean has a statistical standard deviation of about 0.6 $h^{-\frac{1}{2}}$ percent, where h is the fraction of the interval during which observations are available. During about the first three years

of each mission h was ≥ 0.8 but by 1978 had been reduced to ~ 0.25.) During 1976, as reported previously (VA 76) for 1973, 1974, and 1975, there is a quasi-persistent periodic variation of the two counting rates with the synodic period of rotation of the sun (about 26 days). This finer scale variability is superposed on the gross variability which is the more prominent feature of Figure 2. The pairs of small letters a, a'; b, b'; etc. in Figure 3 label corresponding features in the two curves as found most convincingly by overlaying large scale versions of the two separate curves on a light table. The time difference between two corresponding features $\Delta t \equiv t_{10} - t_{11}$ gives a value of the solar wind velocity v in good agreement with directly measured values if one relates the two quantities to the positional data by the formula:

$$v = \frac{\Delta r}{(\Delta t - \Delta\varphi/\omega)} \qquad (1)$$

where $\omega = 1.642 \times 10^{-4}$ deg s^{-1}, the conventionally adopted sidereal angular velocity of the sun at heliographic latitude 17°. The interpretation of this finding (VA 76) is that the 26-day variation is caused by differing magnetic structures (and hence different diffusion coefficients and/or drift coefficients) in quasi-persistent solar wind streams corotating with the sun so as to form an archimedian spiral pattern as viewed in inertial coordinates. During 1977 (Figure 4) the quasi-periodic variation

of counting rates is less clear though there is still a time-delayed general coherence between the rates on the two spacecraft. The reduced level of coherence is presumably attributable to evolution of the magnetic field structure in the increasingly greater Δr between the two spacecraft. The curves for 1977 show much less regularity in the interplanetary structure than that in the preceding years, at least at the large radial distances of these observations. During 1978 (Figure 5) the same tendencies continue, though there was one major coherent feature in April-May 1978 which has been treated in detail in a separate paper (Van Allen 1979).

All data in the foregoing figures have been for detectors C_{10} and C_{11}; the data for two other pairs of detectors B_{10}, B_{11} and D_{10}, D_{11} are essentially identical in nature.

There is a striking qualitative resemblance between annual plots of daily mean values of solar wind velocity v and number density ρ (J. H. Wolfe and J. D. Mihalov, private communication) and those of cosmic ray intensity; i.e., when v and ρ exhibit a regular periodic variation so does the intensity; and when v and ρ exhibit small and/or irregular variability, so does the intensity. But because neither v nor ρ can influence the cosmic ray intensity directly, it appears that this association is only indicative of a further association between the fast-slow solar wind streams and a quantity that can -- namely magnetic structure.

An additional implication is that the gross temporal variations of cosmic ray intensity (Figure 2) are attributable to slow changes in the magnetic structure of the entire heliosphere in three-dimensions. Such changes may not be measurable in or near the solar equatorial plane.

IV. HELIOGRAPHIC LATITUDE DEPENDENCE OF INTENSITY

During mid-February 1976, Pioneer 11 reached a maximum heliographic latitude of +15°.8, the highest value achieved by any spacecraft to date; at the same time the heliographic latitude of Pioneer 10 was +7°.7, following a maximum of +8°.6 in late-December 1974. Cosmic ray data together with the heliographic latitudes for both spacecraft are shown on the same time scale in Figure 6.

The principal conclusion is that there continues to be close coherence between the two counting rate curves, on both large and small time scales. In particular, the cyclic 26-day modulation persists in the Pioneer 11 cosmic ray data and solar wind data throughout the period shown despite the fact that Smith and Tsurutani (1978) observed a marked reduction in toward-away polarity switching in the interplanetary magnetic field vector at Pioneer 11 during late 1975 and most of 1976. It is noted that in February 1976 Pioneer 11 was about 1.0 AU above the solar equatorial plane, a distance of the order of 100 times the gyroradius of a 1000 MeV proton. Thus, it appears that the cosmic ray modulation is identified with the magnetic field structure of fast-slow solar wind streams and not with toward-away magnetic field sectors.

Another aspect of the data of Figure 6 is the casually apparent possibility of determining the heliographic latitude dependence of cosmic ray intensity, though it is clear that any such effect is so small as to be strongly obscured by temporal and spatial variations. After my best efforts to remove the latter variations, I find an apparent latitude dependence of the C_{10}/C_{11} ratio of 0 ± 1.5 percent per 10°. But it should be noted that Pioneer 11 and Pioneer 10 are at greatly different radial distances (3.7 and 9.3 AU, respectively) and it is exceedingly unlikely that a latitude dependence, if any, could be "rigid" over that great a distance. Also the dependence of cosmic ray intensity on latitude presumably has either a maximum or a minimum and hence a zero-slope tangent at the equator. For these reasons the foregoing null result is of little or no significance.

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V. HELIOCENTRIC RADIAL GRADIENT OF COSMIC RAY INTENSITY

The study of the heliocentric radial gradient has now been extended to cover the ranges $1.0 < r_{10} < 18.4$ AU, $1.0 < r_{11} < 8.6$ AU and $1.2 < \Delta r < 9.8$ AU in the same manner as previously described (VA 76). The updated results are shown for the three pairs of detectors in Figures 7, 8, and 9. Assuming that the temporal variations are properly removed by taking the ratios of counting rates at "corresponding" times by the time-lag method (VA 76) and further assuming that $\partial J/\partial r$ is constant, where J is the cosmic ray intensity, I have fit a least squares straight line to the data in Figures 7, 8, and 9 for $\Delta r \leq 8.5$ AU. The results for the radial gradient of intensity, integral for protons $E_p > 80$ MeV (together with helium and heavier ions having the same range in the shield of the detectors), are as follows:

For B_{10}, B_{11} : + 1.94 (± 0.08) percent per AU
C_{10}, C_{11} : + 2.55 (± 0.09)
D_{10}, D_{11} : + 1.91 (± 0.08)

The errors shown are one standard deviation as derived from the r.m.s. departures of the points from the fitted line. The mean value is

$$G = +2.1\ (\pm\ 0.3)\ \text{percent per AU} \qquad (2)$$

The quoted uncertainty in (2) is in the nature of an overall standard deviation, as estimated from the uncertainty of the RTG corrections and from the spread of the three separate determinations quoted above. At least part of the latter is caused by the former.

Even though the range of Δr is only from 1.2 to 8.5 AU, it is clear that the result in equation (2) is appropriate to the range $1.0 < r < 16$ AU. Result (2) is thought to correspond to an "effective" proton energy of several hundred MeV (VA 76).

For $\Delta r > 8.5$ AU, there is a strong increase in all three ratios B_{10}/B_{11}, C_{10}/C_{11}, and D_{10}/D_{11} (Figures 7, 8, and 9). At first glance, this increase might be thought to signal approach to the heliopause. But this is seen to be an untenable conclusion by reference to Figure 2. Intensities at both spacecraft decreased strongly at the time of the April-May 1978 Forbush decrease and have continued to be depressed. The increase of the 10/11 ratios is the result of the fact that the relative decrease was greater at the spacecraft closer to the sun, not to an increase in the absolute rate at the more distant spacecraft. Approach to the heliopause by Pioneer 10 would presumably be accompanied by an increase of the absolute intensity to a value higher than any value previously observed at lesser radii (cf. Introduction). An

alternative interpretation of the unusual rate of increase of the 10/11 ratios in 1978-79 has been suggested by the author elsewhere (Van Allen 1979). Briefly it invokes the possibility that the region of space near the heliographic equator ($\approx$ the ecliptic plane) is replenished in intensity, following a depletion, primarily by translatitudinal diffusion or drift and not primarily by radial diffusion, as usually supposed. Irrespective of the validity of this suggestion, it is clear that the large Forbush decrease of April-May 1978 signaled a substantial disruption of the distribution of cosmic rays within the heliosphere.

No really trustworthy estimate of the position of the heliopause can be derived from the present results but the following line of thought may have some merit: As shown in Figure 2 and our previous work with Explorer 35 (Thomsen and Van Allen 1976), varying solar activity has been observed to cause variations in cosmic ray intensity of the order of a factor of two, deep inside the magnetosphere. Hence, it is reasonable to expect a rather larger ratio, say of the order of five, between the interstellar intensity and that near the sun. At the rate of 2 percent per AU, the corresponding radius R of the heliopause would be given by $(1.02)^R \approx 5$ or $R \approx 80$ AU.

VI. CONCLUSIONS

A summary of this investigation and a brief recapitulation of conclusions are given in the abstract.

Acknowledgement

This work was supported in part by Ames Research Center/NASA contract NAS2-6553 and the U. S. Office of Naval Research. I am indebted to J. D. Mihalov of ARC for sending me unpublished solar wind data and to K. Burton, R. B. Brechwald, E. D. Robison, and J. R. Birkbeck for assistance with computing, typing, and drafting. J. H. Wolfe, C. F. Hall, R. P. Hogan, and J. Dyer of ARC have been especially effective in maintaining spacecraft operations and data reception during the extended missions of Pioneers 10 and 11.

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FIGURE CAPTIONS

Figure 1. Heliocentric ecliptic projection of the trajectories of Pioneer 10 and Pioneer 11 and the orbits of Earth, Jupiter, and Saturn. Black dots are at six-month intervals. The kinks in the trajectories of the spacecraft occur at planetary encounters.

Figure 2. The time dependence of five-day running means of the fully corrected counting rates (in counts per second) of two members of an approximately matched pair of shielded Geiger-Mueller tubes on Pioneer 10 and Pioneer 11. The respective heliocentric distances are given at the bottom and top of the figure.

Figure 3. An expanded plot of the data of Figure 2 for 1976. The pairs of small letters a, a'; b, b'; etc. identify corresponding features of the two curves at varying time-lags caused by corotation of the interplanetary magnetic field structure.

Figure 4. Same for 1977.

Figure 5. Same for 1978.

Figure 6. Time dependence of detector counting rates and heliographic latitudes of the two spacecraft for a period

spanning the time of maximum heliographic latitude of Pioneer 11.

Figure 7. Ratio of the counting rates of detectors $B_{10}(t + \Delta t)$ and $B_{11}(t)$ as a function of difference in heliographic radial distance.

Figure 8. Same for detectors $C_{10}(t + \Delta t)$ and $B_{11}(t)$.

Figure 9. Same for detectors $D_{10}(t + \Delta t)$ and $D_{11}(t)$.

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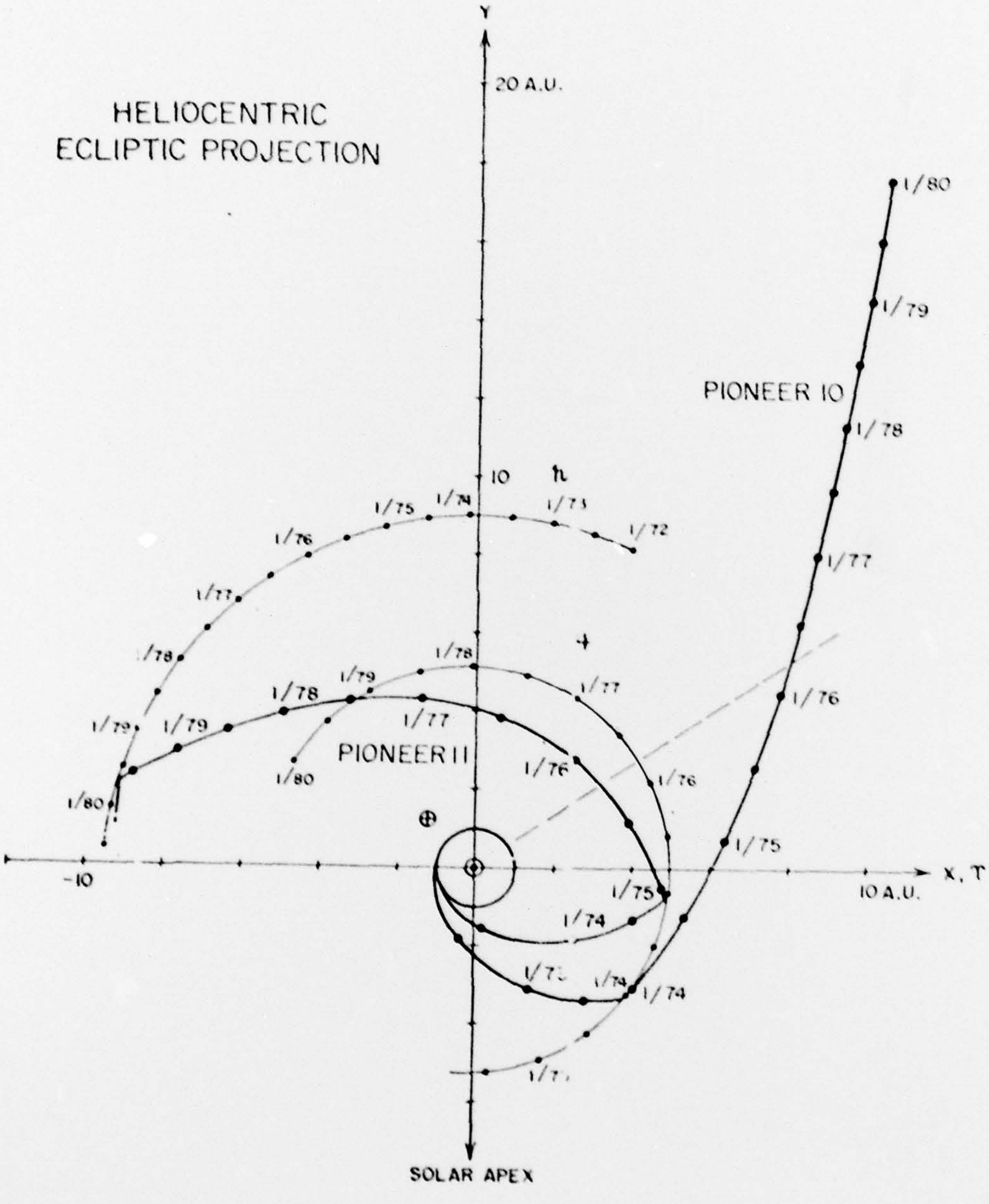

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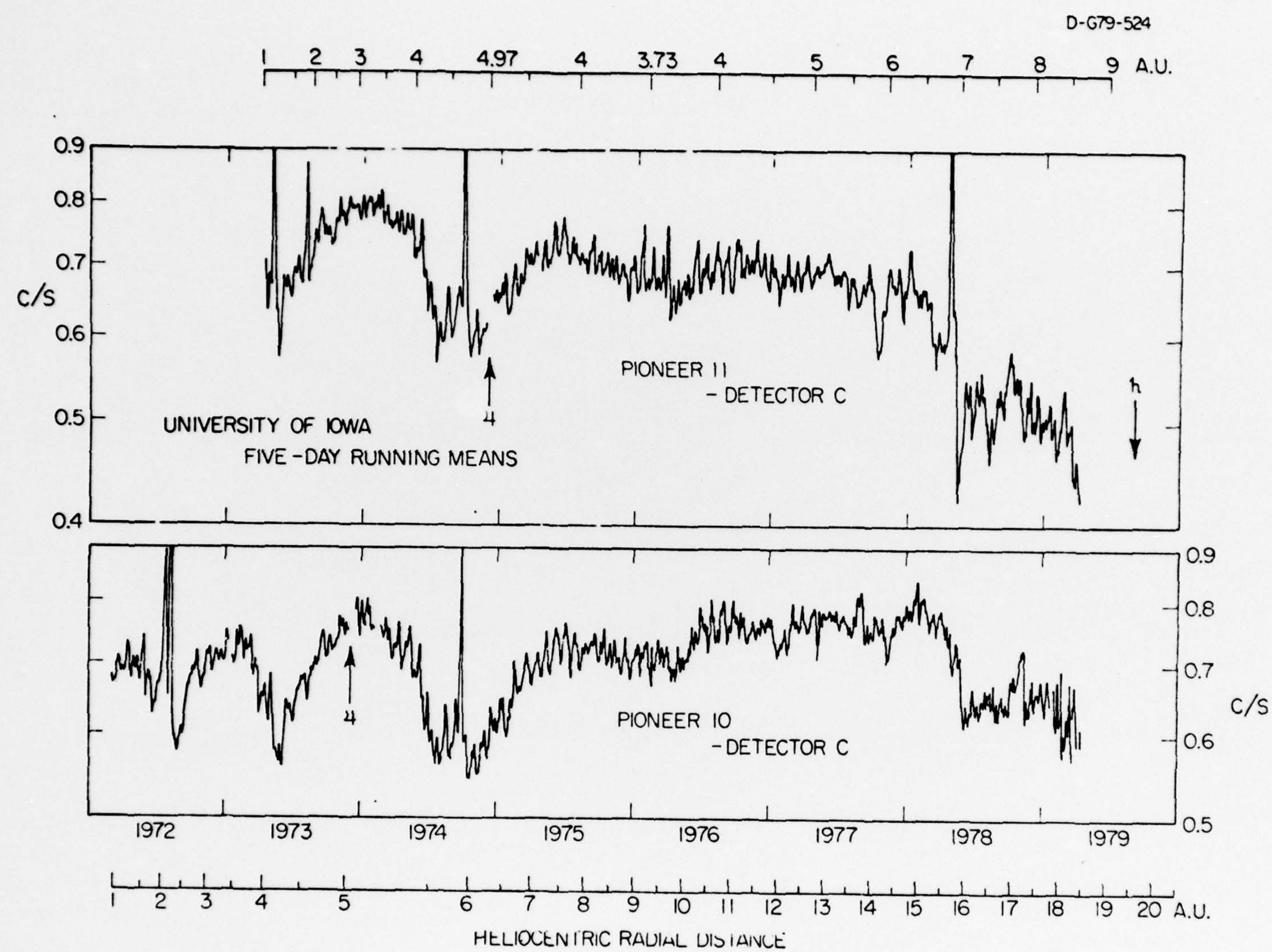
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0.4
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FIVE-DAY RUNNING MEANS
PIONEER 11
- DETECTOR C
4
h
PIONEER 10
- DETECTOR C
0.9
0.8
0.7
C/S
0.6
0.5
1972
1973
1974
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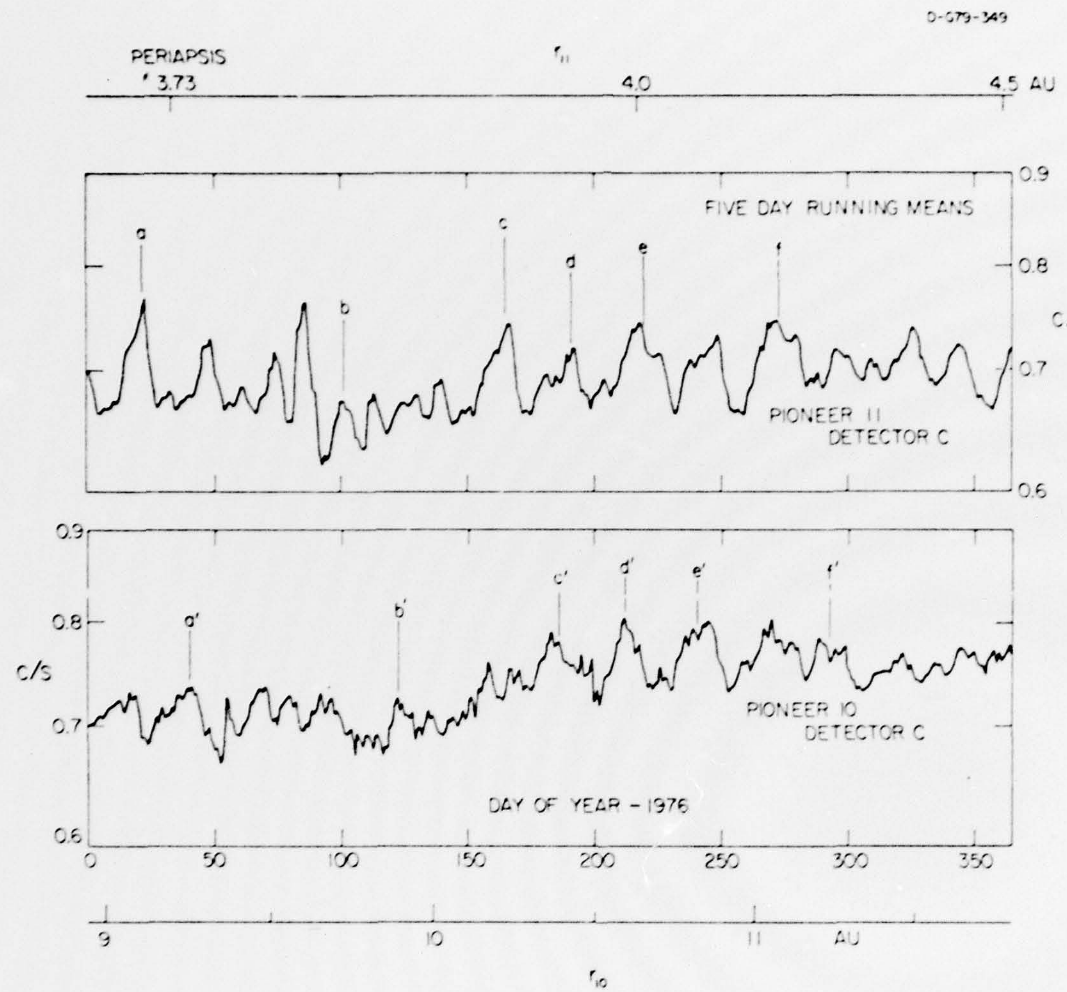
HELIOCENTRIC RADIAL DISTANCE

Figure 2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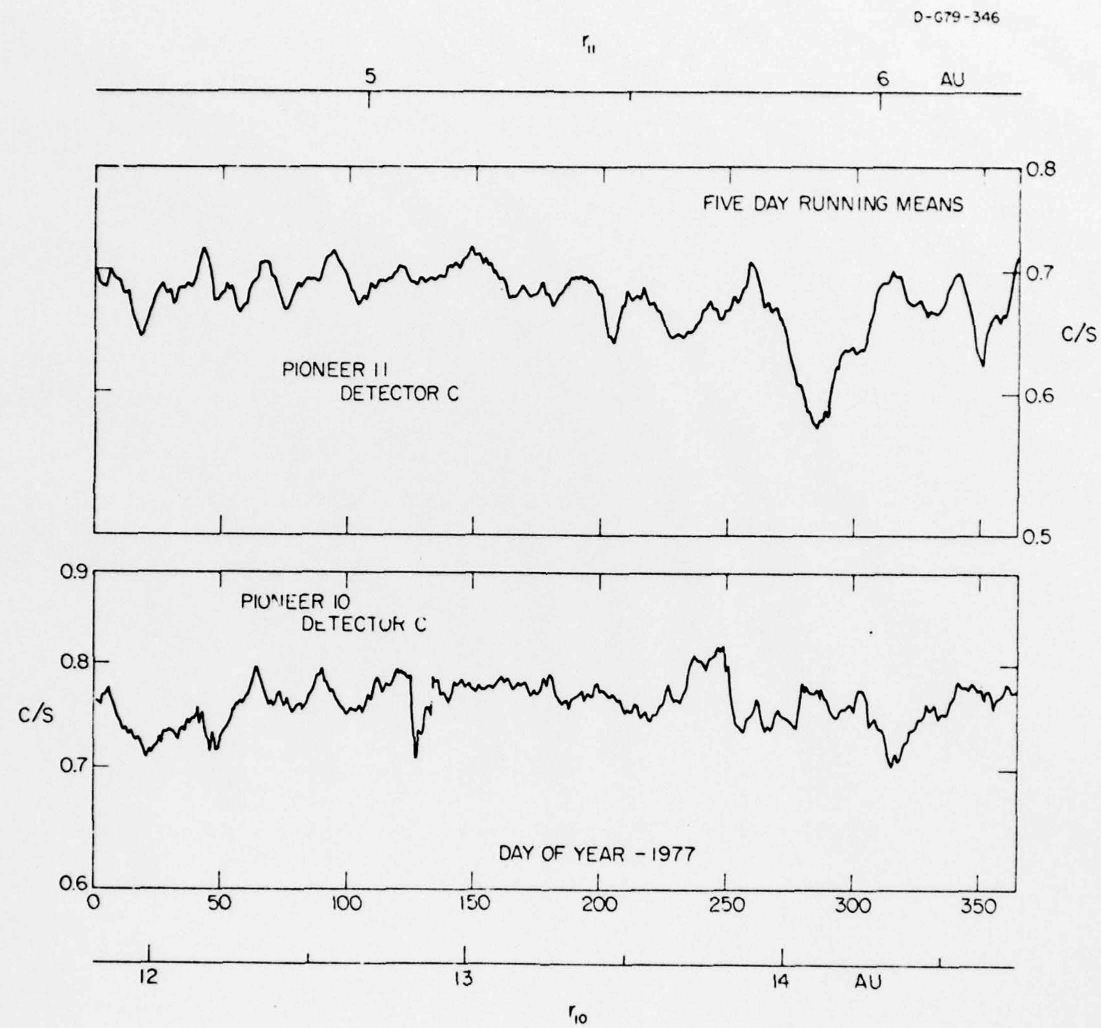
PERIAPSIS
3.73
r_{11}
4.0
4.5 AU
FIVE DAY RUNNING MEANS
a
b
c
d
e
f
PIONEER 11
DETECTOR C
0.9
0.8
0.7
0.6
C/S
a'
b'
c'
d'
e'
f'
PIONEER 10
DETECTOR C
DAY OF YEAR - 1976
0
50
100
150
200
250
300
350
9
10
11
AU
r_{10}

Figure 3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r_{11}
5
6
AU
FIVE DAY RUNNING MEANS
PIONEER 11
DETECTOR C
0.8
0.7
0.6
0.5
C/S
PIONEER 10
DETECTOR C
0.9
0.8
0.7
0.6
C/S
DAY OF YEAR - 1977
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50
100
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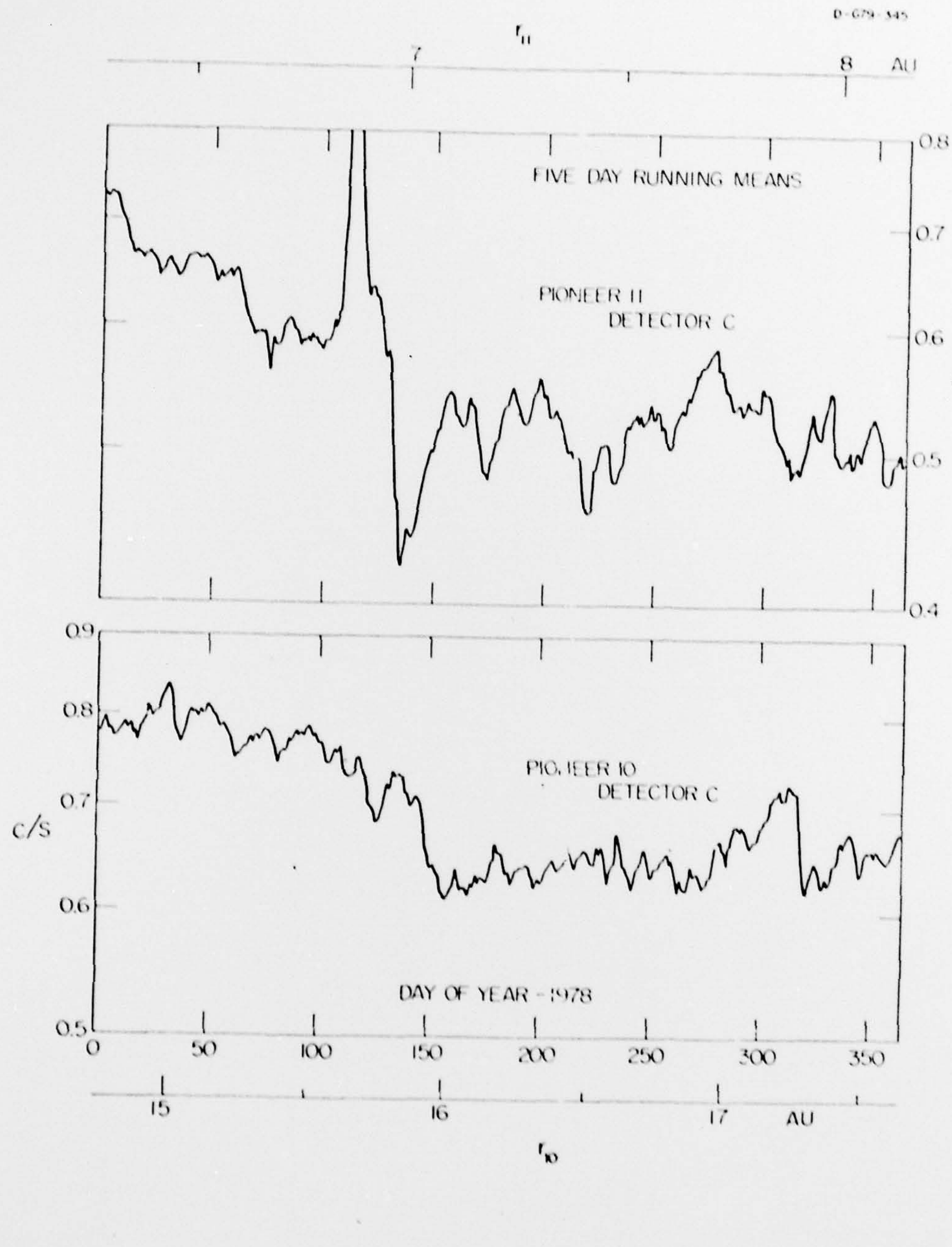
200
250
300
350
12
13
14
AU
r_{10}

Figure 4



D-679-345
r_{11}
7
8
AU
FIVE DAY RUNNING MEANS
PIONEER 11
DETECTOR C
0.8
0.7
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0.5
0.4
c/s
0.9
0.8
0.7
0.6
0.5
c/s
PIONEER 10
DETECTOR C
DAY OF YEAR - 1978
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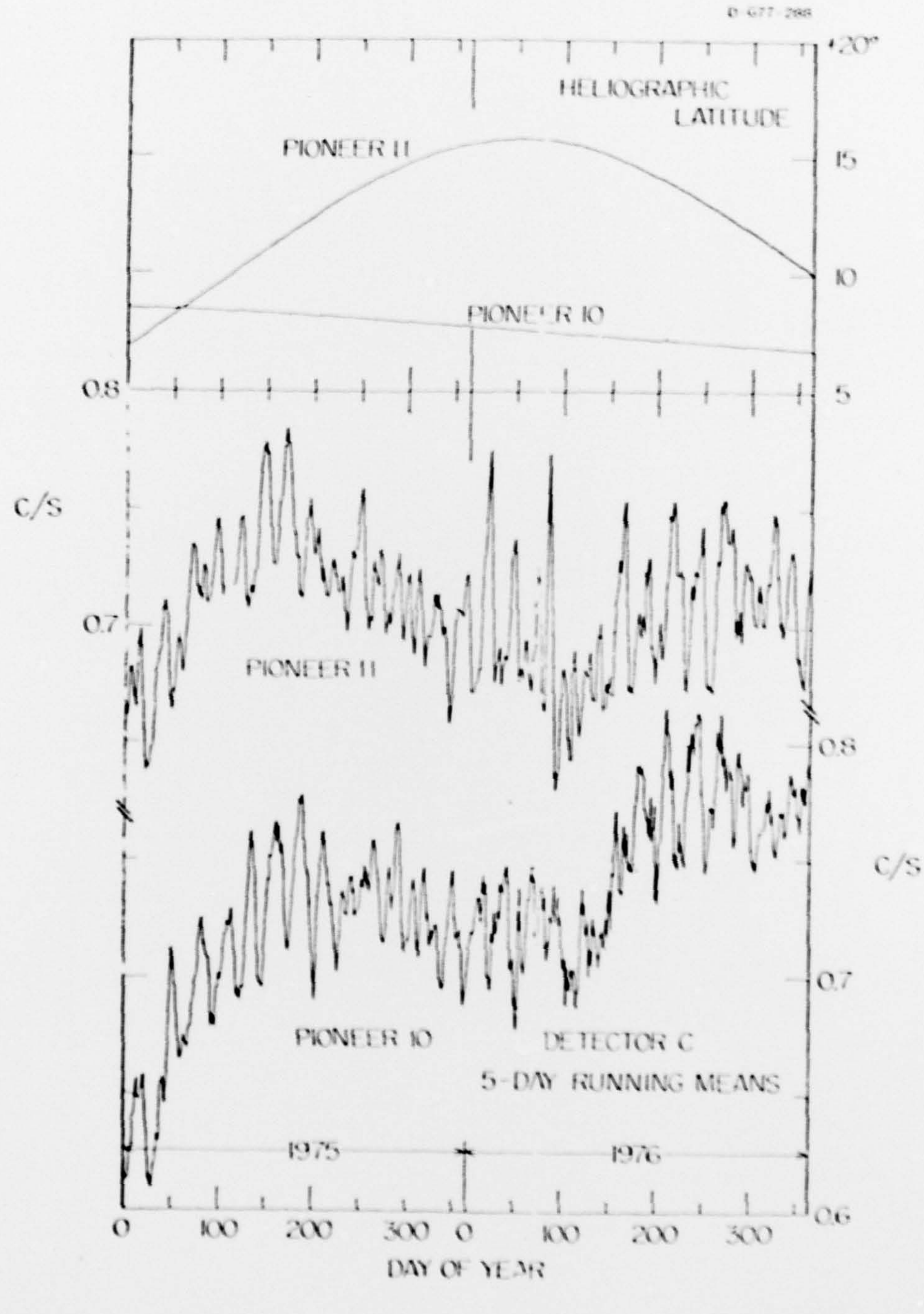
16
17
AU
r_{10}

Figure 5



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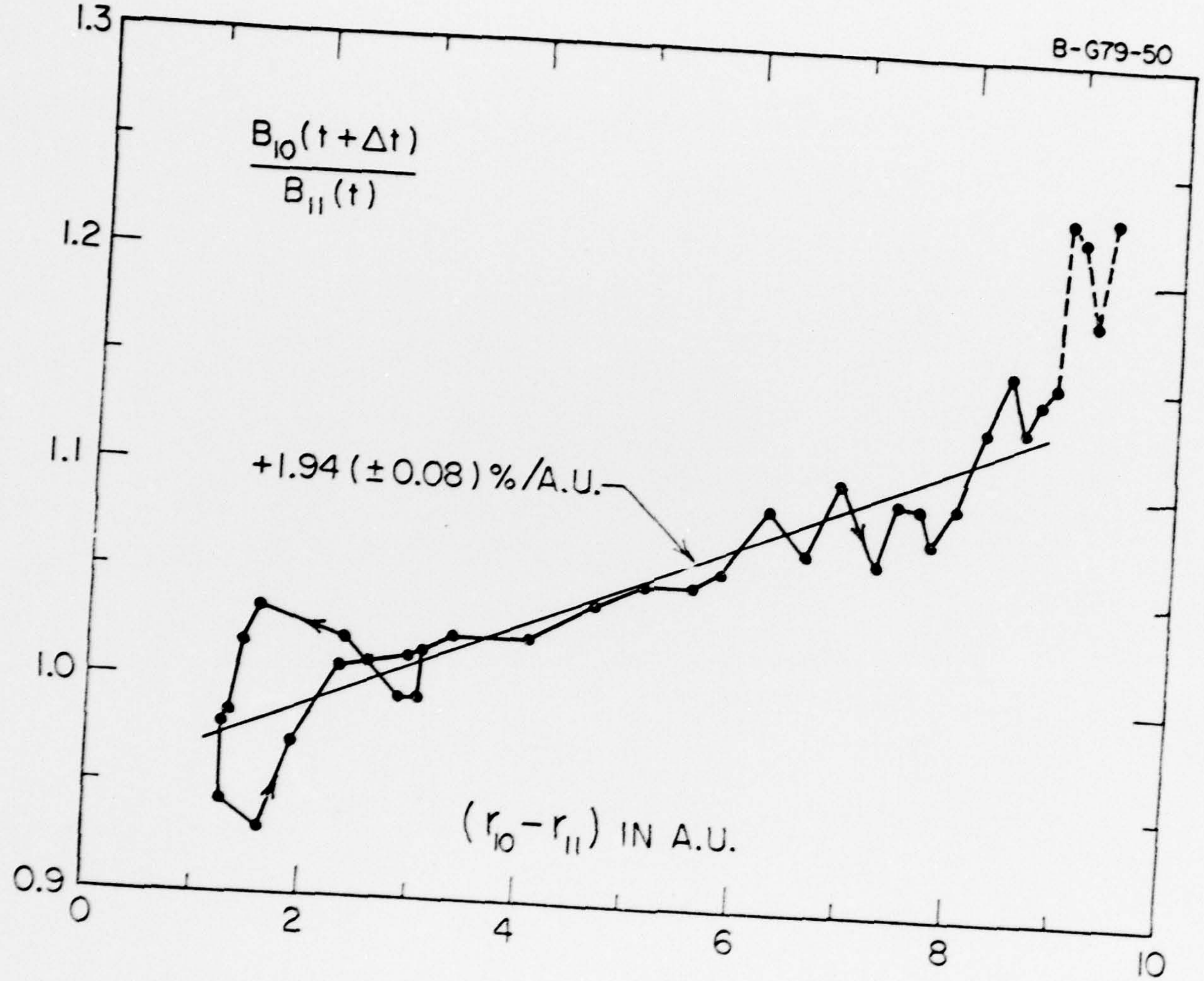
HELIOGRAPHIC
LATITUDE
PIONEER 11
PIONEER 10
20°
15
10
5
0.8
C/S
0.7
PIONEER 11
0.8
C/S
0.7
PIONEER 10
DETECTOR C
5-DAY RUNNING MEANS
1975
1976
0.6
0
100
200
300
0
100
200
300
DAY OF YEAR

Figure 6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$\frac{B_{10}(t+\Delta t)}{B_{11}(t)}$
+1.94 (±0.08) %/A.U.
$(r_{10}-r_{11})$ IN A.U.
1.3
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6
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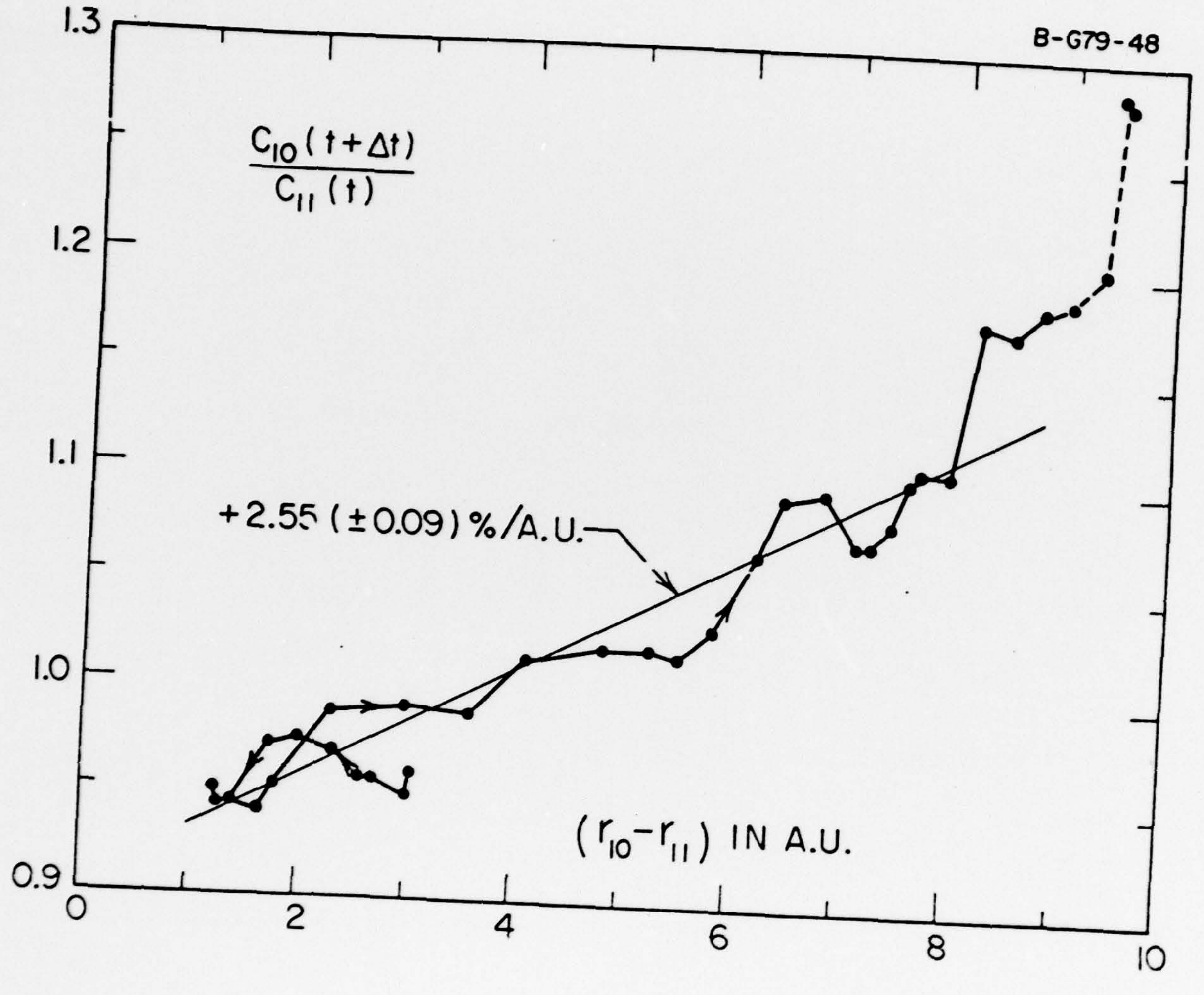
Figure 7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$(r_{10}-r_{11})$ IN A.U.
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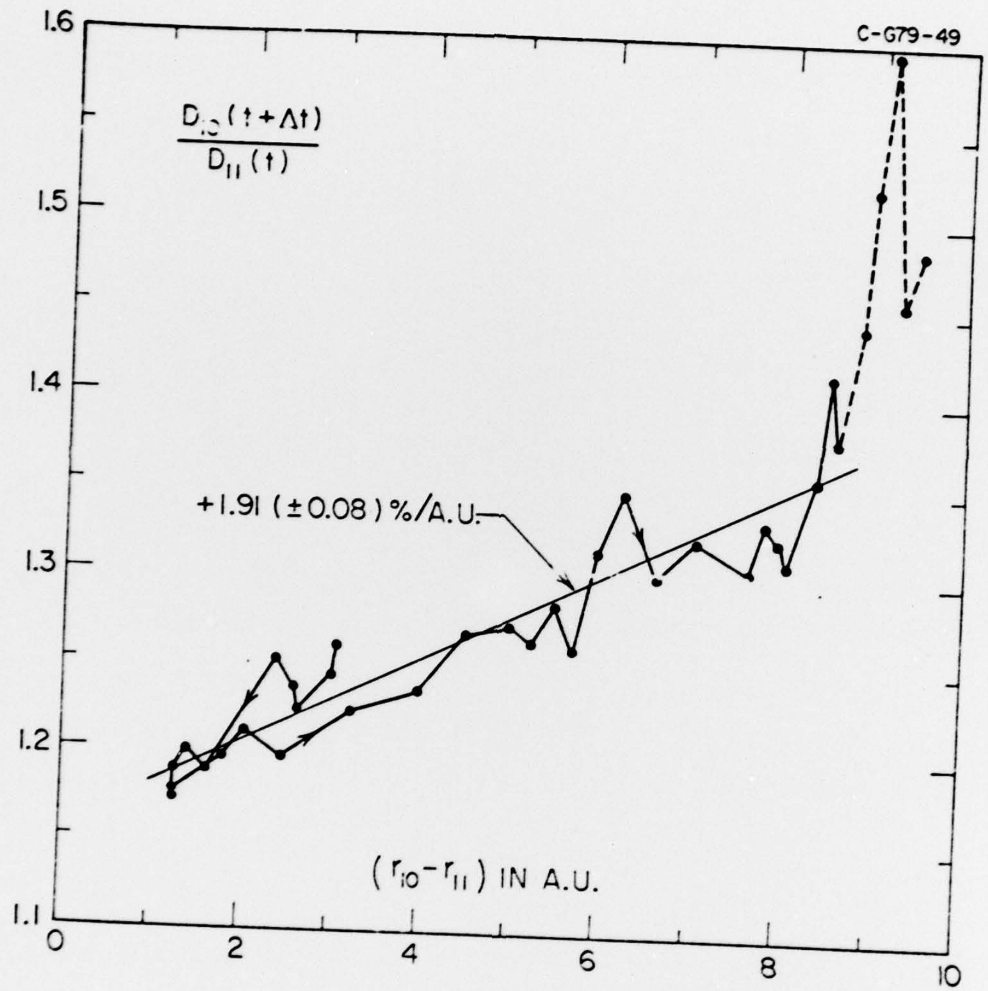
Figure 8


C-G79-49
$\frac{D_{10}(t+\Delta t)}{D_{11}(t)}$
+1.91 (±0.08) %/A.U.
$(r_{10}-r_{11})$ IN A.U.
1.6
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1.4
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1.2
1.1
0
2
4
6
8
10

Figure 9